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A New Power Meter Concept for High Energy Lasers

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Optical Sciences Division

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We describe a new concept for measurement of High Energy Laser (HEL) power. The technique is based upon the phenomenon of optoacoustic detection, which is a sensitive measurement of the sound waves created by absorption of a laser beam of known power with a sample of absorber material for the purpose of absorption coefficient determination. We propose that this process can be inverted to produce an absolute measurement of laser power by using a material for which the absorption coefficient at the laser frequency is

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20. ABSTRACT (Continued)

sufficiently well known. We present a conceptual design and we suggest studies for future development of the concept.

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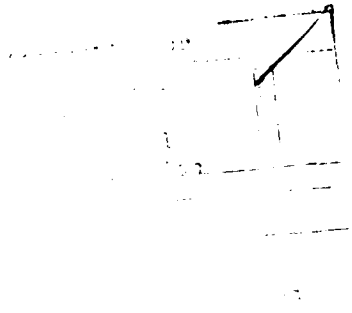

A

A NEW POWER METER CONCEPT FOR HIGH ENERGY LASERS

INTRODUCTION

The output power of a High Energy Laser (HEL) is of great interest for diagnostic and mission assessment purposes. Its measurement also presents the system designer with some unique difficulties. In the conventional method, the beam is directed into a calorimeter in which laser power is converted to a measurable rise in temperature. This redirection and ultimate destruction of the beam preciudes its use for any other purpose during the time the power measurement is made. In addition, a significant proportion of run time, and hence fuel cost, is devoted to this single power measurement. We suggest a measurement process which requires no beam deflection and hence is much more efficient of fuel expenditures. Furthermore, the new method has the potential for providing a continuous check of beam power throughout the entire run of the laser with a resolution typically of tens of Hertz. The full beam is used rather than just a small sample so that, after suitable calibration, it becomes a secondary absolute quantitative measurement. Finally, the envisioned system is capable of replication at a number of stations along the beam to provide real time power history comparisons for post-test analysis and design evaluation.

THE CONCEPT

We introduce the concept by first briefly reviewing the optoacoustic process as a reference. Conventional optoacoustic detection (1) is used to measure, for example, the absorption coefficient of a trace amount of absorber in a background gas. A typical system is shown schematically in Figure 1. A laser beam is chopped at a modest frequency (typically 10-100 Hz). Absorption of this modulated light energy by the trace gas produces almost instantaneous increase in the temperature of the gas. The gas returns to equilibrium by producing acoustic waves of density changes which travel to the sensitive

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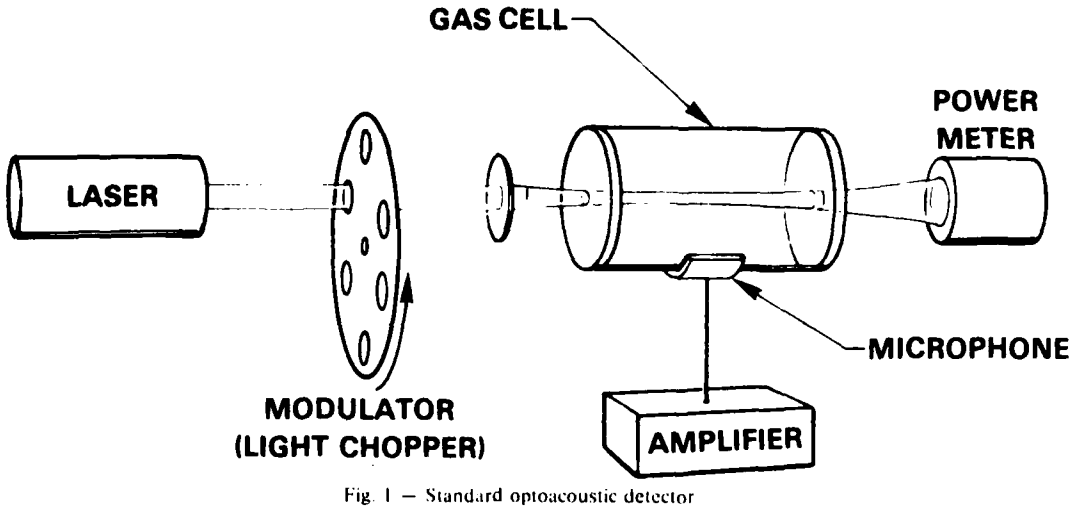

Fig. 1 — Standard optoacoustic detector

microphones at the sound speed of the background gas. The laser beam passes through the cell with no significant reduction of power due to the extremely low total absorption by the trace gas. A power meter is used to measure the laser at the output to the cell.

With this simple description of conventional optoacoustic detection as a reference, we now discuss our suggested modification. In Figure 2, we show our proposed Power Measurement Device (PMD) in which the laser beam is not modulated (a prohibitively difficult task for a HEL beam); nor is a power measured directly by a power meter or calorimeter (a step our system seeks to avoid). Instead, the steady beam passes through the cell essentially unaffected, as in conventional optoacoustic systems. Since a time variation of the energy exchange process between laser and absorber is required to produce the acoustic signal, we turn to the absorbing gas itself as the modulation vehicle. Thus, we propose a flowing gas system in which the concentration of absorbing species is altered periodically along the gas flow path. When the CW laser encounters a region of low or zero absorption, little or no acoustic signal is encountered. When, however, the laser passes through the absorber, an acoustic signal is generated which then can be detected. This process is inverse to the usual process involved with the optoacoustic effect. The physical principles are identical, but the basic intent of the measurement is different, and the active and passive roles of modulation participants are reversed.

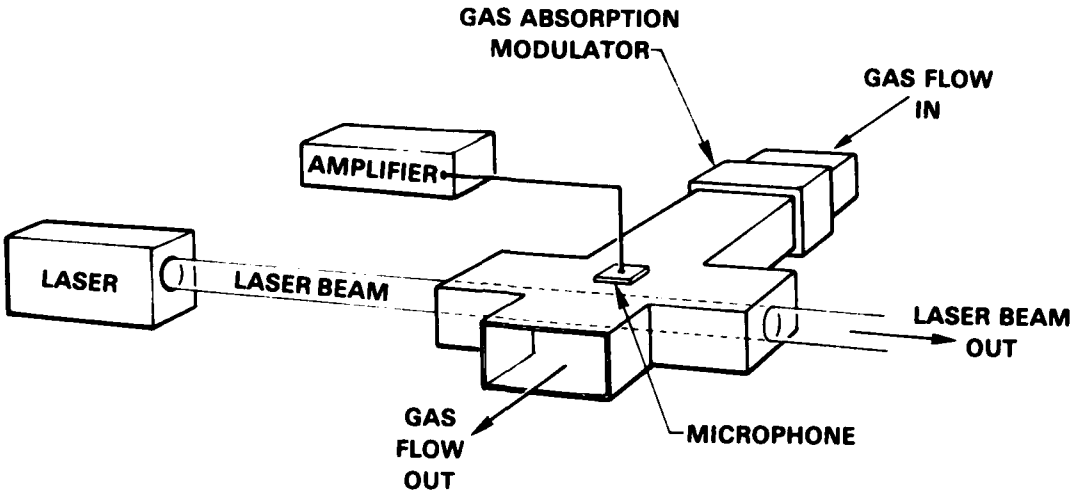

Fig. 2 — Nondestructive laser power measurement device

SCOPING ANALYSIS

A schematic representation of the system is shown in Figure 3. Equally spaced slugs of gas with absorption coefficient α_c are convected with velocity v_c through the laser beam. The length of the slug along the laser beam is L_c and the width of the slug transverse to laser beam is l, as is the width of the laser beam itself. We defer our discussion of just how these gas flows are created to a later section. We assume that the entire beam path is protected by an Environmental Control System (ECS) of total length L_{ECS}, which employs a gas with absorption coefficient α_{ECS} convected transverse to the beam with velocity v_{ECS}. The ECS is designed to prevent thermal blooming (2) of the HEL beam in the optical train. We will use the existence of the ECS to estimate the requirements on the PMD. The perturbation of the laser beam due to thermal blooming is given by (2) the following expression for optical path difference (OPD)

$$\text{OPD} = k(n_0 - 1)\frac{\delta\rho L}{\rho} = -\frac{2\pi}{\lambda}(n_0 - 1)\frac{(\gamma - 1)}{\gamma\rho_0}\left(\frac{\alpha L}{v}\right)\int_{-\infty}^{x} I(x',y)dx', \qquad (1)$$

where $k = 2\pi/\lambda$ is the wave number of the laser, n_0 is the ambient refractive index of the gas, $\delta\rho/\rho$ is the induced relative density change due to laser absorption, L is the path length over which the absorption takes place, γ is the ratio of specific heats, ρ_0 is the ambient gas pressure, α is the absorption coefficient, v is the flow velocity and $I(x',y)$ is the laser power per unit area.

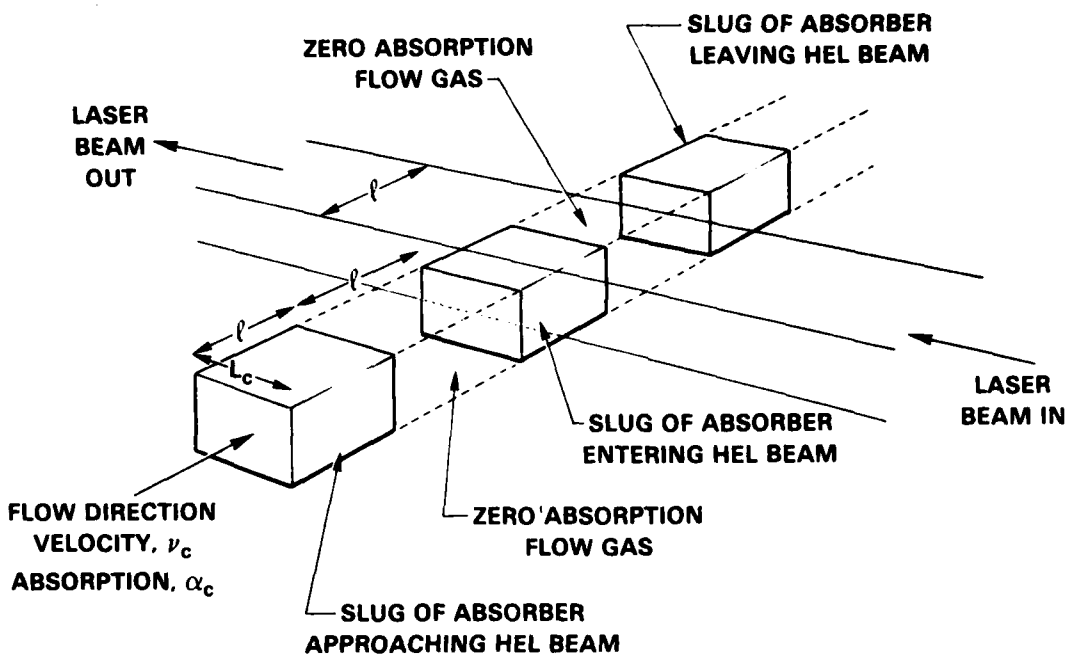

Fig. 3 — Absorbing gas modulation scheme

We assume that the ECS and PMD are identical except for length, L, absorption coefficient, α, and flow velocity, v. Thus, we impose the following condition on the proposed PMD so that it, like the ECS, will not produce thermal blooming

$$\frac{\alpha_c L_c}{v_c} \leqslant \frac{\alpha_{ECS} L_{ECS}}{v_{ECS}} \tag{2}$$

Now, we also require that the velocity of the gas used in the PMD be convected with sufficient speed that at a modulation rate if f slugs per second the beam tube be completely filled with absorber each half cycle, or

$$v_c = fl, \tag{3}$$

where l is the transverse dimension of the beam tube.

Combining Equations (2) and (3) gives

$$\alpha_c \leqslant \left(\frac{L_{ECS}}{L_c}\right)\left(\frac{fl}{v_{ECS}}\right)\alpha_{ECS}. \tag{4}$$

The PMD will occupy only a small fraction of the ECS so that we have, typically,

$$\frac{L_{ECS}}{L_c} \simeq 100. \tag{5}$$

Also, the ECS has flow velocity less than one meter per second, typically, and the nominal width, l, of the laser beam is typically tens of centimeters. Thus for 100 Hertz operation we have

$$\frac{fl}{v_{ECS}} \simeq 30. \tag{6}$$

Finally, we see that to avoid thermal blooming by the addition of a PMD station the beam, we must be careful to seed the main flow gas of the PMD with an absorber that satisfies

$$\alpha_c \leq (3 \times 10^3)\alpha_{ECS}, \tag{7}$$

where we have combined Equations (4)-(6).

Now, since the detected acoustic signal is proportional to α_c, equation (7) implies that we will have a great deal of latitude in the design of a high signal-to-noise PMD by choosing a suitably large value of α_c which, nevertheless, still obeys the inequality of equation (7).

ABSORBER MODULATION SCHEMES

We turn to a discussion of some possible ways of inducing the absorber concentration modulation on the flowing gas.

A. Species Modulation

The first conceptual scheme is a direct fluid-mechanical technique. We will not discuss the, perhaps difficult, engineering implementation of this scheme. A rapid action valve is required to insert gas slugs at the rate of f per second with a 50% duty cycle. A schematic is shown in Figure 4. The main flow is made up of a non-absorbing gas (perhaps supplied from the ECS stores) which entraps the injected absorbing component during the open half cycle of the fast action valve. Spoilers are arranged downstream to assure good mixing prior to entrance into the plenum and hence into the beam path. Some very preliminary work using an aquarium aerator pump pointed out one problem with this method. The pumping action itself causes a variation in the gas pressure, independent of whether the gas is absorber or background carrier. This variation is measured by the microphone as an acoustic signal at the pump frequency. Some clever engineering would be required to remove this acoustic interference.

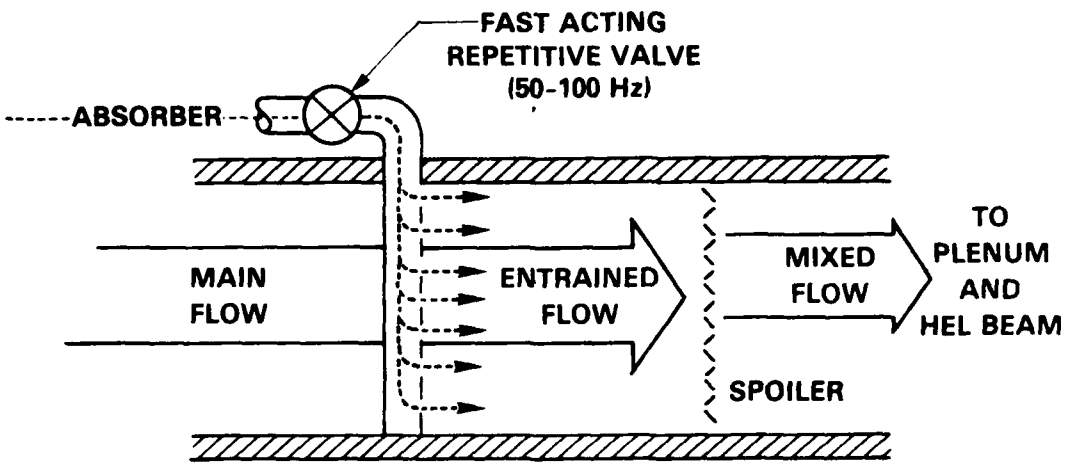

Fig. 4 — Mechanical absorber modulation scheme

B. Ultraviolet Dissociation

A second method is optical in nature and is shown in Figure 5. Here we envision use of a single flow system employing a gas which has already been mixed with absorber. The gas is made non-absorbing by periodic application of, for example, a flash lamp which depopulates the absorbing transition in the gas. This method requires that the relaxation of the excited absorber not occur before the gas flows into the HEL beam. This probably implies that the flash lamp be located right at the HEL beam position since relaxations are typically too rapid to allow the excited species to be convected into the beam path before de-excitation occurs. A modification of this approach is to use an intense UV source to disassociate the absorbing molecules periodically.

It is not difficult to scale the performance of such a device by using parameters for an existing DF laser spectrophone recently used to measure methane absorption in Argon (3). In the following we derive a relation for the acoustic signal as a function of HEL power, uv energy fluence, and methane concentration.

The absorbing species is provided during the *off* cycle of an ultraviolet flashlamp or doubled laser pulse. During the *on* cycle the methane is dissociated via the reaction $CH_4 + \gamma \rightarrow CH_2 + H_2$. Neither of the above products absorbs DF, hence the modulation.

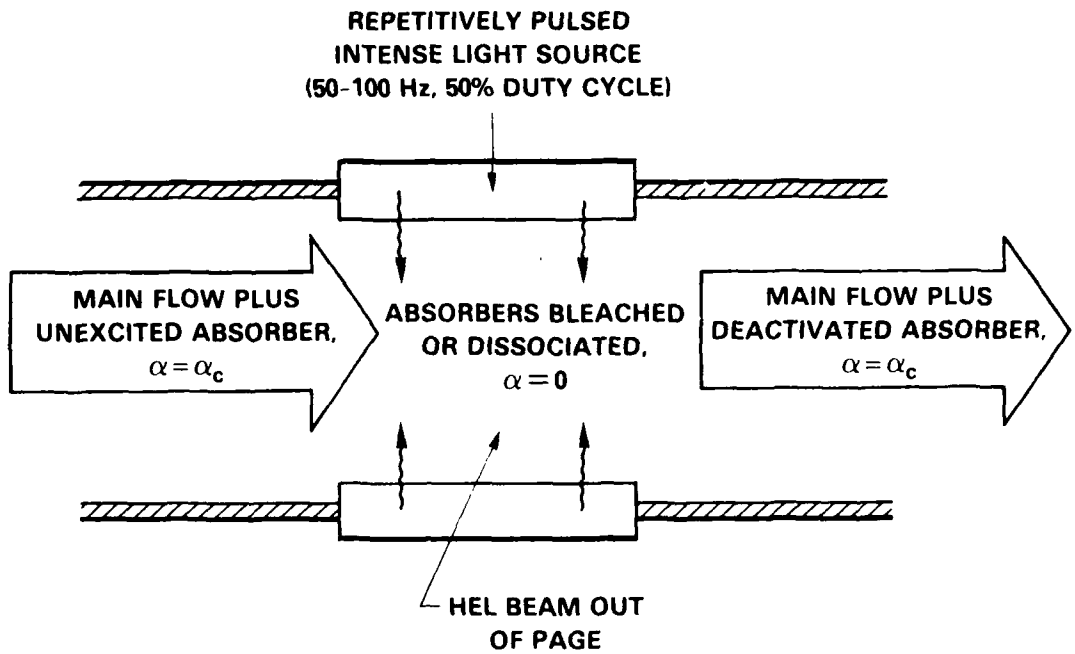

Fig. 5 — Optical absorber modulation scheme

The acoustic signal is proportional to the product of the laser beam power absorbed and the modulation M. (Our most recent spectrophone had a Noise Equivalent Power (NEP) of about 0.1 μwatt for a 1 Hz bandwidth.) If P is the power of the DF laser beam, then

$$\text{DF beam power absorbed} = P[1 - \exp(-\kappa_{DF} l_{DF})],$$

where the absorption coefficient is

$$\kappa_{DF} \approx 1.3 \times 10^{-5} \frac{cm^{-1}}{\text{torr}} p_{CH_4}.$$

Now, since $\kappa_{DF} l_{DF} << 1$, we have

$$\text{DF beam power absorbed} = (1.3 \times 10^{-5})\, P \times p_{CH_4} \times l_{DF}. \tag{8}$$

The modulation is given by,

$$M = \frac{\text{number } CH_4 \rightarrow CH_2 + H_2 \text{ reactions}}{\text{number of } CH_4 \text{ molecules}}. \tag{9}$$

At 1250 Å$\approx$ 10 eV, each pulse with energy ξ millijoules contains $6.25 \times 10^{14}\, \xi$ photons. The number of dissociations this causes is related to the ambient uv flux absorbed,

$$\frac{\text{number dissociations}}{cm^2} = \frac{6.25 \times 10^{14}}{A} \xi \times (1 - e^{-\alpha n p l}), \tag{10}$$

where α is the ultraviolet absorption of methane near 1250Å (Ref. 4) and is given by, $\alpha = 500\ \text{cm}^{-1}$ / atm $\approx 0.66\ \text{cm}^{-1}$/ torr, the quantum efficiency, $\eta \approx 0.4$, and the length of the uv beam is equal to HEL beam width and is given by $l_{uv} \approx 10$ cm, so that

$$\alpha \eta p l_{uv} = 2.64\ p_{CH_4}. \tag{11}$$

The number of CH_4 molecules per cm^2 in the uv beam is:

$$3.54 \times 10^{16} \times p_{CH_4} \times l_{uv} \tag{12}$$

Substituting (10) - (12) into (9) gives:

$$M = 0.018 \frac{\xi}{A} \times (1 - e^{-2.64p}) \times \frac{1}{p_{CH_4}} \times \frac{1}{l_{uv}}. \tag{13}$$

The acoustic signal is then from (13) and (8)

$$\text{Acoustic Signal} = 2.34 \times 10^{-7}\ \underline{P} \left(\frac{\xi}{A}\right) \frac{l_{DF}}{l_{uv}} (1 - e^{-2.64p})$$

Now

$$\frac{l_{DF}}{l_{uv}} \approx \frac{1}{10}$$

and

$$\underline{P} \approx 1\ M\ \text{watt}$$

Hence,

$$\frac{\text{Acoustic Signal}}{M\ \text{watt}} = 2.34 \times 10^{-2} \left(\frac{\xi}{A}\right) (1 - e^{-2.64p})\ \text{watts} \tag{14}$$

$$\text{for } p_{CH_4} \approx 1\ \text{torr} \Rightarrow 0.023 \left(\frac{\xi}{A}\right)\ \text{watts}$$

$$\text{for } p_{CH_4} \approx 1\ \text{ppm} \Rightarrow 4.6 \times 10^{-5} \left(\frac{\xi}{A}\right)\ \text{watts}.$$

Note that at 0.1 ppm (below the impurity level of CH_4 in Argon) a uv energy fluence of 1 millijoule/cm^2 at 1 Megawatt of IR power gives 4.6 μwatts of acoustic signal, roughly 50 X the noise level at a 1 Hz bandwidth. Hence a very diluted methane in Argon mixture of say 10 ppm could give a response time of 0.01 seconds with a signal/noise of far greater than 10/1.

Figure 6 gives a graphic interpretation of Equation (14) assuming 1 mjoule/cm^2 of uv fluence. A methane concentration of less than 0.1% (1000 ppm) will satisfy Equation (7). If the HEL beam is multifrequency such as a chemical laser, than the choice of absorber becomes more difficult. The gas must absorb over a broadband of laser transitions. In addition, the power on each transition is rapidly changing in time as the gain medium cascades through the vibrational-rotational transitions. In some cases, the HEL may be designed to operate over a wide range of powers by alteration of the oxidizer flow rate to the laser cavity. This alone produces differing relative power weighting among laser lines for each power setting.

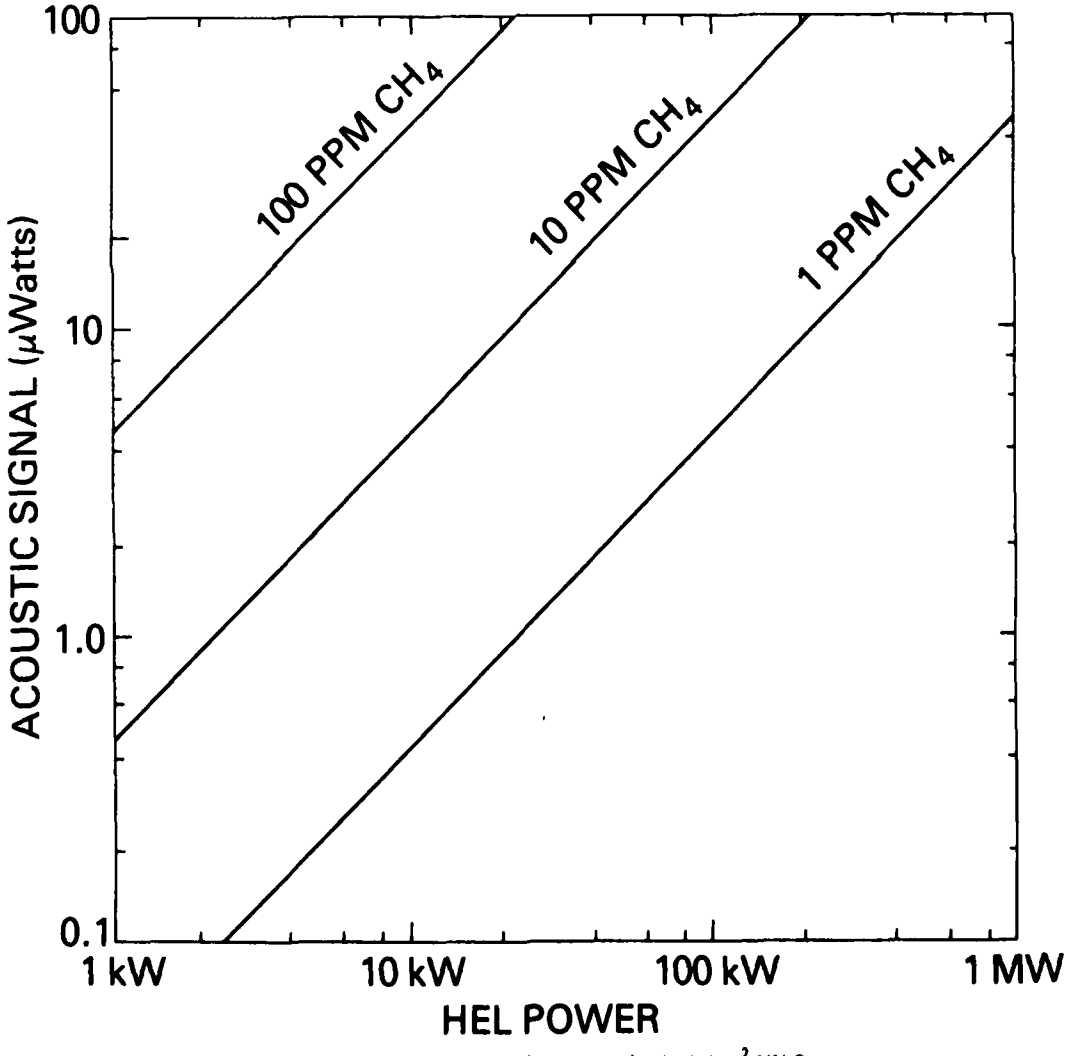

Fig. 6 — Acoustic signal vs HEL power at 1 mjoule/cm^2 UV fluence

For the case of mechanical modulation the broadband absorption associated with the nitrogen continuum near 3.8 μm might be a suitable candidate for the DF chemical laser PMD design. Perhaps the unexcited lasing specie itself (for example, DF) is a suitable candidate for all schemes mentioned above. These are clearly all issues which must be addressed early in the development of these concepts to the detailed engineering phase.

OTHER ISSUES

The proposed system must be calibrated initially. One source is high power calorimeter which has been related to an NBS standard. Another calibration scheme is use of lower power lasers, conventional power meter techniques and a parametric variation of PMD gas flow velocity, absorber concentration per slug, and PMD cell length to effect a suitable relation for scaling to high power with confidence.

The environment of a high power laser, especially a chemical laser with its large steam ejector for low pressure cavity operation, is a very noisy one. Thus great care must be taken in the design of the acoustic detector to reduce the ambient noise to a minimum. This problem is important, but not fundamental, and we assume that careful engineering of the final design can overcome this difficulty.

Note that since this concept is a feed-through system, more that one PMD can be employed along the beam path to directly monitor and compare power loss contributions of various elements in the optical train. Although we specifically addressed application of this concept to the problem of non-interference, non-destructive measurement of HEL beam power, clearly one could also apply this method to monitor power of lower power samples of the HEL beam such as will exist in the system diagnostic area. One simply trades the reduced power for enhanced absorber concentration in the design. Also lower velocity flows could be employed here to effect cost savings on ECS supplies.

The cost of PMD construction does not appear to be prohibitive, and is certainly much less than a high power calorimeter and switch. Operational costs will have minimal impact as well. The main flow

gas for the PMD could be relayed from the ECS supply storage. Reference to the above formulas relating PMD to ECS flow conditions and volumes required indicate that each PMD employed will require less than a 10% increase in the utilization of ECS gas supplies. Finally, the cost savings of HEL cavity fuel and oxidizer will be significant by elimination of the run time dedicated only to calorimetry via conventional beam interruption. Typical cavity fuel and oxidizer costs for high energy lasers are typically a few thousand to tens of thousands of dollars per second of run time.

CONCLUSION

We have proposed a non-destructive HEL beam power measurement which promises to be accurate, efficient and of low cost to build, maintain and operate.

The remaining issues which require further study before a final detailed design could be attempted can be readily addressed in small scale experiments using the currently available technology of optoacoustic detection.

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